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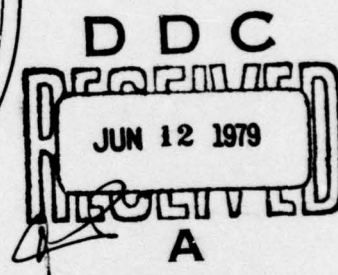
TECHNICAL INFORMATION BULLETIN
79-6

CRITERIA FOR THE EVALUATION OF
TWO-DIMENSIONAL CODING TECHNIQUES
FOR USE IN DIGITAL FACSIMILE TERMINALS

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MAY 1979

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report describes proposed criteria to evaluate the relative technical/ economic merits of competing two-dimensional compression algorithms submitted by member nations to CCITT Study Group XIV for adoption as an international standard. In addition, appendix A contains a draft proposed contribution by the United States of America to the CCITT entitled "Criteria for the Evaluation of Two-Dimensional Coding Techniques for use in Digital Facsimile Terminals".

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CRITERIA FOR THE EVALUATION OF

TWO-DIMENSIONAL CODING TECHNIQUES FOR

USE IN DIGITAL FACSIMILE TERMINALS

MAY 1979

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FOREWORD

Among the responsibilities assigned to the Office of the Manager, National Communications System, is the management of the Federal Telecommunication Standards Program which is an element of the overall GSA Federal Standardization Program. Under this program, the NCS, with the assistance of the Federal Telecommunication Standards Committee, identifies, develops, and coordinates proposed Federal Standards which either contribute to the interoperability of functionally similar Federal telecommunication systems or to the achievement of a compatible and efficient interface between computer and telecommunication systems. In developing and coordinating these standards a considerable amount of effort is expended in initiating and pursuing joint standards development efforts with appropriate technical committees of the Electronic Industries Association, the American National Standards Institute, the International Organization for Standardization, and the International Telegraph and Telephone Consultative Committee of the International Telecommunication Union. This Technical Information Bulletin presents an overview of an effort which is contributing to the development of compatible Federal, national, and international standards in the area of digital facsimile standards. It has been prepared to inform interested Federal activities of the progress of these efforts. Any comments, inputs, or statements of requirements which could assist in the advancement of this work are welcome and should be addressed to:

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CRITERIA FOR THE EVALUATION
OF TWO-DIMENSIONAL CODING
TECHNIQUES FOR USE IN
DIGITAL FACSIMILE TERMINALS

December 4, 1978

FINAL REPORT

submitted to:

NATIONAL COMMUNICATIONS SYSTEMS
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ARLINGTON, VIRGINIA 22204

contracting agency:

DEFENSE COMMUNICATIONS AGENCY

Purchase Order: DCA100-79-M-0034

submitted by:

DELTA INFORMATION SYSTEMS, INC.
259 WYNCOTE ROAD
JENKINTOWN, PA. 19046

TABLE OF CONTENTS

Appendix A--Draft copy of "Criteria for the Evaluation of
Two-Dimensional Coding Techniques for use in Digital Facsimile
Terminals"

1.0 Introduction

This document summarizes the work performed by Delta Information Systems, Inc. for the National Communications Systems agency of the U. S. Government under Purchase Order DCA100-79-M-0034. The Statement of Work of the subject Purchase Order required the determination of "the criteria for evaluating the technical/economic merits of various data two-dimensional algorithms/coding techniques for digital facsimile terminals being proposed for adaption as an international standard by the CCITT."

The Statement of Work described the background of this contract as follows:

> The International Telegraph and Telephone Consulta-
> tive Committee (CCITT) Study Group (SG) XIV is respon-
> sible for the development of facsimile standards in
> the international arena. Many of the parameters
> relating to interoperability of facsimile apparatus
> have been identified and agreed upon. However, one
> area which remains to be resolved involves compression
> algorithms/coding techniques; more specifically two
> dimensional compression algorithms. During the period
> 11-15 December 1978, Working Party 2 of CCITT SG XIV
> will meet in Geneva, Switzerland. The subject of two
> dimensional compression algorithms will be an agenda
> item. The Japanese have already submitted a contri-
> bution on this subject. Other contributions are
> anticipated at the 11-15 December meeting. What will
> be lacking as a common criteria against which to
> evaluate the relative technical/economic merits of
> competing two dimensional compression algorithms.

The purpose of this contract is to provide these common criteria.

The work on the subject contract was performed by Richard Schaphorst and Neil Randall of Delta Information Systems, Inc. and guided by Dennis Bodson, the Contractor's Technical Representative from the National Communications System. We also wish to acknowledge the helpful discussions with the following members of the EIA TR-29 Facsimile Systems and

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Equipment Engineering Committee: Charles Jacobson, Robert Krallinger,

Tim McCullough, A. Schmidt, Lou Cartolano, and Forrest Smith.

2.0 Summary of the Work Performed

Work on the subject contract was divided into the three major tasks

discussed in the paragraphs below--(1) Identification and Definition of

Evaluation Criteria (2) CCITT Contribution (3) Final Report.

1 - Identification and Definition of Evaluation Criteria

This task occupied the major portion of the contract. During this

effort, basic documents such as those References listed in Appendix A

(Section 4.0) were reviewed to determine their applicability to the issue

at hand. Several CCITT documents mentioned four criteria for the evalua-

tion of data compression techniques as listed below.

- Compression Factor
- Error Sensitivity Factor
- Cost of Implementation
- Commonality with other Facsimile Codes

These criteria were discussed with various members of the EIA Facsimile

Committee and there was general agreement that they be proposed in the

CCITT paper.

Following the identification of the evaluation factors, each was

next defined. During the definition process, many alternative specifica-

tion concepts and approaches were considered. Sections 3.0, 4.0, 5.0

and 6.0 present the various alternatives which were evaluated for each

criteria and the rationale for selecting the particular definitions which

are proposed. Section 7.0 discusses the various procedures and techniques

which were considered for ranking the relative importance of the criteria.

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As the various definitions were evolved during the course of the contract, great benefit was derived from discussion with various members of the EIA Facsimile Committee.

2 - CCITT Contribution

The Statement of Work calls for the submittal of a draft copy of a "U. S. contribution to CCITT Study Group XIV". . ."for evaluating competing two dimensional compression algorithms/coding techniques." It further specifies that the "contribution be furnished at the time of submission of the final report." In compliance with this requirement, the draft copy is included as Appendix A. It should be noted that a copy of this proposed contribution was submitted to the C.O.T.R. on November 20, 1978.

3 - Final Report

The final report summarizing all work performed on the subject control is submitted herewith. In addition to describing the work done, Section 8.0, which contains recommendations for further study, has been included.

3.0 Compression Factor

One of the most critical parameters in the selection of a compression coding technique is the compression factor which measures the ability of the algorithm to reduce redundancy in the input data and thereby reduce the number of bits required for transmission. Several terms have been used to represent this compression parameter -- compression ratio, compression factor, and reduction factor to name a few. In addition, some experimenters have chosen to describe the compression performance entry in terms of transmission time over a given data link. In this paper the term Compression Factor (CF) has been chosen and is defined as the number of picture elements in the document to be transmitted divided by the number of code bits required for transmission of that document.

There are three issues related to the Compression Factor which require further discussion -- (1) selection of the test documents, (2) G3 machines, (3) G4 machines. These issues are analyzed in the paragraphs below.

● Selection of Test Documents

It is generally recognized that the Compression Factor must be measured using actual representative graphic material as the input as opposed to hypothetical patterns of test data. It would be desirable for the test document(s) to represent the full range of material which might be handled by the G3/G4 facsimile equipment. For example, users may occasionally transmit a half-tone image or a continuous tone photograph though it was not designed for that purpose.

In addition, it would be desirable for the test document(s) to reflect, as accurately as possible, the statistical distribution of the documents which would be actually transmitted. For example, if most of the transmitted documents contained typed text, then a code which has a relatively high compression

ratio for textual data should be favored. Unfortunately there is very little published information on the distribution of documents transmitted through facsimile networks.

Another criterion for the selection of test documents is precedent - ie. what documents have been used for similar measurement purposes in the past. The 8 CCITT test documents shown in Figure 1.C, and listed below, have achieved a wider range of acceptance than other documents and are also somewhat representative of the pages likely to be transmitted through the G3/G4 machines.

Document No.	Description
1	Business letter with logo and signature
2	Circuit diagram
3	Invoice
4	Typed French text
5	Text and Figures
6	Graph
7	Japanese characters
8	Handwritten memo

Consequently, the 8 CCITT documents have been selected for use in this proposal.

The Frech PTT Administration has scanned these 8 CCITT documents at both the standard and high resolutions as specified for Group 3 machines. They have also quantized each pel to be either black or white and stored the resultant image on magnetic tape. Further, the French PTT has provided copies of these tapes to experimenters in the data compression field so that facsimile performance data can be compared on a meaningful basis. For these reasons, it is recommended that the proposed measurements be performed using the tapes supplied by the French PTT Administration.

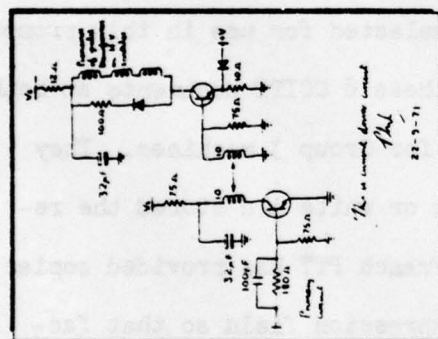- CF Measurement for G3 Machines (CF_3)

It is desirable to measure the CF using simulated conditions which are as realistic as possible. Since the CF for G3 machines can be significantly
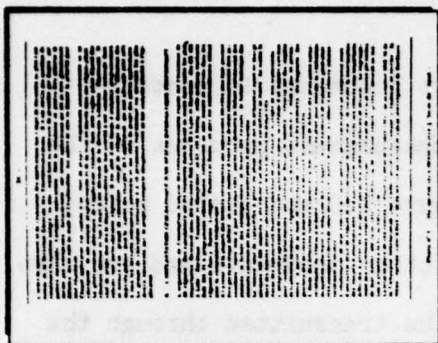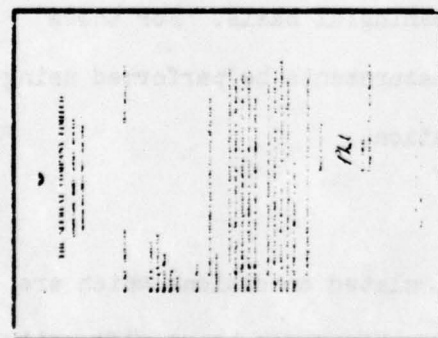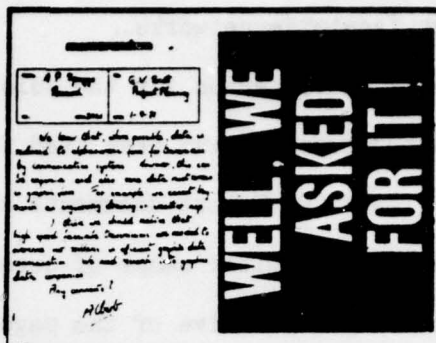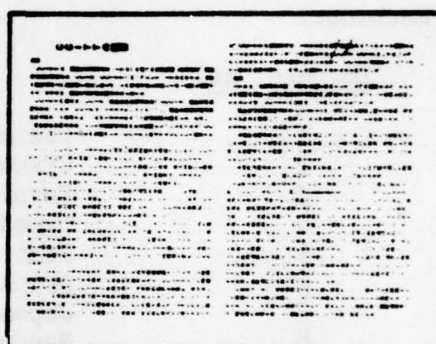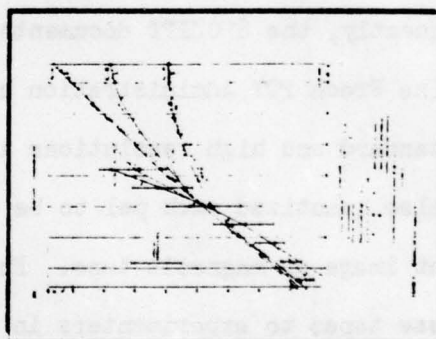
DOC NO. 4
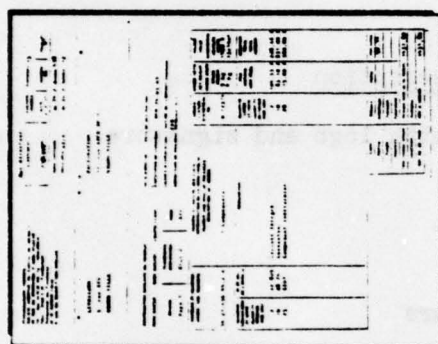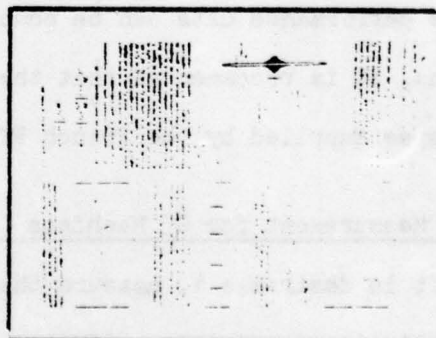
DOC NO. 3

DOC NO. 3

DOC NO. 7

DOC NO. 2

DOC NO. 6

DOC NO. 1

DOC NO. 5

Figure 1.0 CCITT Standard Test Documents

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impacted by the number of transmitted Fill bits they must be included in the simulation. In order to simulate the Fill function the minimum line transmission time and the transmission bit rate must be specified. Since

ms is the standard minimum line transmission for G3 machines it was selected for the proposal. A data rate of 4800 bits/sec. was chosen, since it is considered typical for G3 application.

It is further recommended that the G3 simulation include all synchronization bits such as the beginning-of-message, end-of-line, and end-of-message. It is not expected that these bits will significantly impact the measured CF parameter, but it is desirable to insert them into the transmitted code bits so that the simulation output magnetic tape can be used directly for measurement of error sensitivity. In addition the inclusion of these synchronization does make the measured CF more precise.

- ## CF Measurement for G4 Machines (CF_4)

The G4 facsimile machines will be operating over Public Data Networks. In this application it is not anticipated that Fill bits will be required. In addition the error rate of the data networks are expected to be sufficiently low that error sensitivity will not be a significant factor in code selection. Therefore there will be no need to prepare a magnetic tape with synchronization bits for subsequent error sensitivity analysis. For these reasons it is proposed to measure the CF for G4 machines using transmitted code bits which contain no synchronization or fill bits.

- ## Measurement Data

It is proposed to measure CF_3 and CF_4 for both the 3.85 and 7.7 lines/mm resolution for all 8 CCITT test documents. The potential desirability of computing average CF parameters for the 8 test documents was considered.

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However, this was rejected because it would infer an equal weighting to each of the test documents, which is probably not a valid assumption.

4.0 Error Sensitivity

In addition to Compression Factor, it is important to evaluate coding techniques for their sensitivity to transmission errors, particularly for the Group 3 machines. The typical application for Group 3 machines involves transmission over dialed telephone lines using modems that do not have error control. Under these conditions transmission errors can become significant, and with some coding techniques the errors could be propagated over a large part of the picture, causing unacceptable results. With the Group 4 machines, the transmissions themselves will be provided with error protection, so that few errors will reach the facsimile decoder. Thus, the evaluation of error sensitivity is recommended only for Group 3 machines. However, since it is expected that the Group 3 and Group 4 codes will be the same, it may be desirable to evaluate a proposed Group 4 coding technique to determine if it is also suitable for Group 3 machines.

It was felt that both an Objective and a Subjective measure of error sensitivity was required. Fortunately, both can be obtained without an increase in simulation effort. The Objective measure is a numerical value representing the number of pels that are represented incorrectly by the decoding algorithm, divided by the number of bits that were in error in the corresponding transmission. The Subjective measure will consist of presenting, for committee evaluation, images that have been corrupted by errors, in order to determine the nature of the image errors, and how noticeable or objectionable they are.

4.1 Test Documents

In order to minimize the computer time required for the error sensitivity measurement, not all of the test documents used for the CF tests

will be used for error sensitivity measurements. Two of the eight CCITT test documents have been selected for error tests. Both are mostly typed text, which is expected to constitute a large portion of the total traffic. CCITT Test Document 1 was selected as typical of documents having high compression factors, and should serve to exhibit errors as black marks in the large white areas of the document. CCITT Test Document 4 was selected as typical of documents having low compression factors, and should serve to exhibit possible intelligibility problems. Each of these Test Documents will have been encoded in the course of measuring the CF, so the encoding need not be repeated. The encoding used for measurement of CF_3, which includes synchronization and fill bits, will be used, since transmission errors are associated with Group 3 machines. The encodings for standard and high resolution will be used in the error sensitivity test.

4.2 Error Patterns

To measure the error sensitivity, the encoded bit streams are corrupted by an error pattern that reverses selected bits. In order to provide a repeatable test, it is not possible to use random error sequences generated by the computer performing the simulation, since each such sequence would be different. It would be possible to generate a single random sequence to be used by all experimenters, but this would not provide an important characteristic of real circuit noise: the fact that errors appear in bursts. It would be possible to produce artificial error patterns with burst characteristics, but it was judged easier and more realistic to make a record of an actual error pattern for use by all experimenters. The error pattern should be obtained by transmission

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over switched telephone links that are expected to be typical for the Group 3 machines. Therefore, it was recommended that 4800 bits/sec with a V27 ter modem be used.

The bit error rate should be high enough to cause a large number of bit errors in each image, in order to minimize the number of images that must be processed to obtain a statistically significant sample. Note that processing time is almost entirely dependent on the number of images processed, and hardly at all on the number of bit errors encountered. The fact that the error rate is higher than that usually encountered on high-quality circuits is not important, since the effect of a lower error rate can be extrapolated from the high error rate case. An upper limit on the error rate is placed by the requirement that a single line should not frequently encounter more than one error burst. If this occurred, it would be difficult to extrapolate the test results to lower error rates. The number of bits per line must be at least 48 even in blank areas because of the required fill bits, and could be 432 bits if the compression factor is 4. The error rate that has been selected is 10^{-3}, or an average of 1 error in 1,000 transmission bits, which is less than 1 per line, even in "busy" areas. The probability of a line of 432 bits encountering more than one error if the bit errors are selected <u>at random</u> is only 0.07. This becomes even lower when the fact that errors occur in bursts is considered. For example, if the average number of error bits in a burst is 5, the probability of more than one <u>burst</u> in 432 bits at 10^{-3} error rate becomes 0.0035. Thus, it appears that the occurrence of more than one error burst per line will be a relatively rare event if the bit error rate is 10^{-3}, so that

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extrapolation to lower error rates can be easily made.

A different error rate could be used for the Objective and Subjective tests. This could be done if the error rate chosen for the Objective test produced an image that was beyond recognition. However, the results obtained by the French PTT Administration, at an error rate of about 10^{-3}, show reasonably good results, at least good enough to make judgments of relative performance. Therefore, it is recommended that an error rate of about 10^{-3} be used for both Objective and Subjective tests. This will minimize the amount of computer simulation required.

The length of the error pattern was specified as 10^6 bits, which is expected to be longer than any one encoded image.

The Federal Republic of Germany has already made recordings of error patterns meeting all of the above requirements.[7] A standard set of these measurements should be used for these tests. The approximately 1000 error positions in 10^6 bits should be provided on magnetic tape or punch cards for use by experimenters.

4.3 Sample Size

The number of images that are processed in the Error Sensitivity test must be sufficient to provide a statistically meaningful estimate of the true error sensitivity. However, the number of images that are processed must be minimized to keep the amount of computer time required for the simulation within bounds. While only two Test Documents have been chosen for error sensitivity testing, any number of images may be processed, simply by applying a different error pattern to the two Test Documents. In fact, the same error pattern can be used to produce different

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received images simply by shifting the error pattern relative to the transmitted bit stream so that errors impinge on different code words, thereby producing an independent evaluation of the error sensitivity.

It is proposed that the transmission be delayed by 1,024 bits relative to the error pattern on each test of the same Test Document. This shift is intended to be larger than the number of bits used to represent a line, but small enough so that succeeding tests use substantially the same bit errors, which will minimize the fluctuations from one trial to another. Also, the delay should not be a multiple of 48 bits, the minimum number of bits that can represent a line, so that the error pattern should impact a different part of the code each time it is used.

The accuracy of the estimate of error sensitivity will depend, to a large extent, on the number of relatively rare events, such as errors in EOL codes, that can be expected in the documents that are processed. It is proposed that for the standard resolution images, three runs be made of each Test Document with different phases of the error pattern. Some numerical calculations will serve to illustrate the accuracy that can be expected in the estimation of the Error Sensitivity Factor (ESF).

The numbers used in this calculation are derived from Table 2 of the Federal Republic of Germany paper.[7] The average figures for the EIA Code are used, but the same figures for the ITC Code are not much different. The average number of lost pels on a line due to an error burst causing incorrect run length codes is almost 500. If a burst of 5 errors is assumed, the number of pels in error per bit error is 100. For standard resolution and a compression factor of 10, the transmission will be 183,859 bits long, and will attract about 184 bit errors at an error rate of 10^{-3}. Thus, there will be about 184 X 100 = 18,400 pel errors due to incorrect

run length codes. Because of the large number of events involved in each document, it is expected that the ESF due to incorrect run length codes will be quite stable from document to document. The bulk of the variation in ESF is expected to arise from less frequent events, each of which causes a large number of pels to be in error. The principal event of this type will probably be a missing EOL or a false EOL. The data of Table 2 indicates an average of about 2 of each of these events per document, at a bit error rate of about 5×10^{-4}. The bit error rate must be doubled to make it comparable to the proposed rate of 10^{-3}, so the average number of each of the events per documents will also double to 4. The actual number of events in a document should be Poisson distributed, since there are many chances for the event to occur, but each chance has a very low probability. Therefore, the standard deviation of the number of events is the square root of the average number of events. For this case, the standard deviation would be two events. If it is assumed that the number of pel errors that result from each event is 1,728, then the average pel errors per document from all causes becomes

$$18,400 + (4 \times 1728) = 25,312 \text{ pels}$$

while the standard deviation becomes:

$$2 \times 1,728 = 3,456 \text{ pels}$$

which is 14% of the average. If the average of three documents is taken, the standard deviation is reduced by $\sqrt{3}$, or to 8% of the average. This is a reasonably good accuracy and will not be improved substantially by a modest increase in the number of documents processed. Further, it should

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be noted that the error in the ESF estimate will be reduced by:

- a lower compression factor
- a higher ESF due to incorrect run lengths alone
- less than 1,728 pel errors per EOL event
- consideration of both missing and false EOL events

Therefore, it is concluded that three runs of the standard resolution document should provide a reasonable accuracy in the estimation of the ESF. For the high resolution case, there should be more transmission bits, transmission errors, EOL codes, and EOL errors, thus reducing the variations in the ESF measurement. Therefore, it is recommended that only two runs be made on each document for high resolution scanning.

Having obtained the ESF for each of the three runs, ESF_1, ESF_2, ESF_3, the average is calculated to be:

$$ESF_{avg} = \frac{ESF_1 + ESF_2 + ESF_3}{3}$$

The best estimate of the variance of the population is given by:

$$\sigma^2_{pop} = \frac{1}{n-1}\left[\sum_{i=1}^{n}(ESF_i)^2 - \frac{(\sum_i ESF_i)^2}{n}\right] = \frac{1}{n-1}\left[\sum_i(ESF_i)^2 - n(ESF_{avg})^2\right]$$

and the estimate of the variance of the sample average is:

$$\sigma^2_{avg} = \frac{1}{n}\cdot\frac{1}{n-1}\left[\sum_i(ESF_i)^2 - n(ESF_{avg})^2\right]$$

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For three documents the standard deviation of the estimate of the average ESF is:

$$\sigma_{avg} = \left[\frac{(ESF_1)^2 + (ESF_2)^2 + (ESF_3)^2 - 3(ESF_{avg})^2}{6} \right]^{\frac{1}{2}}$$

For two samples proposed for the high-resolution case, we have:

$$\sigma_{avg} = \left[\frac{(ESF_1)^2 + (ESF_2)^2 - 2(ESF_{avg})^2}{2} \right]^{\frac{1}{2}}$$

The standard deviation of the estimate of the ESF is useful as a check on the adequacy of the sample size and gives an indication of whether measured differences between the ESF's of contending coding techniques are statistically significant. As a rule of thumb, the difference between the average ESF's should be equal to or greater than the sum of their standard deviations to be considered statistically significant.

4.4 Evaluation

The images produced by decoding the error-laden transmission are compared, pel by pel, with the original image. A count is made of the number of pels that differ in "color" from the original. This is divided by the number of bit errors that actually impinged on the transmission, to yield the ESF for that trial. Normally, no movement of received pels relative to the original image will be permitted to achieve a closer match with the original. An exception to this rule is that if an entire line is added or dropped, usually due to EOL code errors, a penalty will be

assessed only for the first received line that is matched with the incorrect original line. In order for the comparison algorithm to keep track of which line is which, each EOL should by numbered in the original transmission and in the received transmission. This number would not of course be available to the decoding algorithm, but only to the comparison algorithm.

Perhaps the most difficult decision made during this study was the degree to which various error correction schemes could be utilized to reduce the ESF, both for the Objective measure and the Subjective measure. It is possible to define the CF for a Coding Technique, quite apart from the decoding algorithm, as long as it can be shown that there is, in fact, an algorithm that will exactly produce the original image. On the other hand, the ESF cannot be evaluated from a knowledge of the coding technique alone; the decoding algorithm must also be known. The proposed standards are for coding techniques only; each manufacturer can use any decoding approach he wishes to. Hence, there is an inherent difficulty in estimating the ESF.

Clearly, the coding technique must include a decoding algorithm in order to evaluate it for error sensitivity, despite the fact that only the encoding is to be standardized. The question is, how much latitude can be given to the decoding algorithm to correct errors with sophisticated schemes? One side of the argument says that only that amount of decoding actually required to correctly reproduce an image from an error-free transmission should be used. The rationale for this is that it is the encoding that is to be standardized and tested, and therefore any error correction will only mask the inherent qualities of the coding technique.

We have rejected this approach for the following reasons:

(1) It is difficult and arbitrary to separate a decoding algorithm into those parts required for error-free reception and those designed to correct for transmission errors.

(2) Coding techniques that provide a controlled amount of redundancy for error control will be unfairly punished, since their compression factor will be low because of the increased redundancy without the commensurate gain due to a lower error sensitivity.

(3) It will favor encoding techniques that minimize exposure to errors by minimizing the length of critical words, such as EOL, rather than adding controlled redundancy.

Therefore, it is proposed that any decoding algorithm proposed by an experimenter be accepted, providing that it is fully disclosed and documented. This will allow the full use of whatever redundancy is provided in the transmission to provide error control. If excessively complex error correction schemes are proposed, they will be penalized under the "Ease of Implementation" criteria. It is expected that more than one decoding algorithm will be proposed for each coding technique, in order to demonstrate that the coding technique can be used with decoding algorithms of varying complexity. In this case, each decoding algorithm must be evaluated for error sensitivity.

Subjective evaluation must be done with high-quality images of the received pictures. If possible, they should all be made on the same type of equipment, in order to eliminate the subjective effects of contrast and resolution.

5.0 Cost of Implementation

The cost to implement the candidate coding techniques is one of the important parameters in the selection process. Cost is also one evaluation criterion which would seem to be expressible in hard quantitative form. Unfortunately, it is unrealistic to expect, or request, equipment design or cost information from organizations proposing a compression algorithm. The competitive aspect of the facsimile business totally inhibits the availability of such data. Even if cost information were available from manufacturers, it is likely that the data would vary over a wide range due to the great variability of design and manufacturing philosophies. For example, the design objectives for different companies would differ greatly from the standpoint of systems reliability, human factors, size, ease of repair, and power, to name a few. These different design philosophies and objectives have far-reaching implications as far as equipment cost is concerned. A similar type of variability occurs in the manufacturing area. For example, the size and efficiency of the manufacturing facility has a large impact on equipment cost. There is also a question of the production volume and the time frame of the production.

Due to the wide range of cost factors enumerated in the paragraph above, it is very difficult for a committee such as the EIA or CCITT to develop hard, meaningful cost data to aid in the selection process of a compression technique. It is understood however, that each committee member will, in his own way, be estimating the costs of the candidate techniques; and these relative costs will, and should, weigh heavily

in the decision process.

Above and beyond the cost factors discussed above, is one important
issue which deserves special attention - patent and royalty considerations.
It is generally agreed that it is critically important that a proposed
coding technique be free of any royalty considerations.

6.0 Compatibility with Other Facsimile Machines

It is obviously highly advantageeous to the facsimile community and systems users for different classes of machines to be compatible, i.e. interoperable. Since the compression coding tachnique is a key factor in compatibility, it is clearly desirable to consider this issue when selecting a code for Group 4 and the two-dimensional extension of Group 3.

Three different types of compatibility factors are present:
1. Group 3/Group 4 2. Group 3 (1 dimensional)/ Group 3 (2 dimensional)
3. Machines with greater document width. Each of the compatibility issues is discussed below.

Group 3/Group 4

Since the Group 4 machine will operate over data networks, the bit error rate of the communication channel will be very low. For this reason it would be possible to consider two-dimensional codes for Group 4 equipment which are much more sensitive to transmission errors than might be considered for Group 3 machines. This difference in error sensitivity may be sufficiently fundamental that different two-dimensional codes would be chosen for the two systems. It must be recognized, however, that if two different codes were selected, a significant penalty would be paid in the cost to achieve compatibility. In other words, it would clearly be desirable for the Group 4 machine and extended Group 3 systems to employ the same code, and this factor must be carefully considered in the evaluation process.

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Group 3 (1-dimensional)/Group 3 (2-dimensional)

There is obviously a very strong motivation for the basic Group 3 machine with the one-dimensional code to be compatible with the optional Group 3 machine with the two-dimensional code. If necessary, compatibility can be achieved by implementing systems with both codes so they can communicate with either type of equipment. However, it may be possible to select a two-dimensional code which uses the one dimensional code as a functional element. Stated another way, it may be possible to select a two-dimensional code which is an extension of the one-dimensional code. If this could be done, the cost of equipment compatibility would obviously be reduced.

Machines with Greater Document Width

It is desirable to select a compression algorithm which can be economically extended for application to documents wider than that for the Group 3 machines. For example, it may be desired to double the document width so that a total of 3,456 pels/line would be transmitted. It would be advantageous for the code for the wide document to be merely an extension of the normal width code for reasons of compatibility and cost minimization.

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7.0 Relative Importance of the Criteria

One major purpose of this document is to assist persons or committees in selecting a standard facsimile algorithm. Toward this end, it would be very helpful to rank the four evaluation criteria in terms of their relative importance. Unfortunately, this is very difficult to do for three reasons. First, various committees and committee members have widely varying perspectives and orientations relative to the criteria. Secondly, the criteria are not independent, but in many cases interact in complex ways. The third difficulty concerns the fact that two of the criteria (cost, compatibility) are difficult to quantify. These three points are discussed in the paragraphs below.

Varying Perspective

Different committees and committee members can have widely varying background and perspectives relative to the evaluation criteria. For example, it is inevitable that facsimile manufacturers and common carrier organizations would view the evaluation parameters differently. In addition, the market orientation of a vendor will greatly affect his position. For instance, a company which manufactures products in large volume and stresses conventional picture quality would view the situation differently from a vendor who stresses the low volume/high quality market. Also, different vendors have varying technological strengths in other facsimile subsystems (such as sophisticated adaptive modems) which would affect their position. All of these factors make it extremely difficult to adopt a clear ranking of the evaluation factors in terms of their relative importance.

Criteria Interdependency

It is very difficult to rank the evaluation criteria due to the large degree of interdependency and interaction which exists between them. For example, some facsimile systems can automatically reduce the transmission rate to the point where an acceptable error rate is achieved. This results in a trade-off between error sensitivity and compression. Another trade-off could exist between error sensitivity and implementation cost. At one extreme could be a compression system which is very sensitive to transmission errors but which employs a very complex post-decoder, error-reduction scheme to minimize the visual effect of errors. At the other extreme could be a coder which inserts sufficient redundancy into the transmitted code to correct for some transmission errors. In this case, the system is relatively insensitive to channel errors, may be less expensive, and would have a reduced compression ratio.

Qualitative Criteria

Although the cost and compatibility criteria are potentially quantifiable, it was pointed out in Sections 5.0 and 6.0 that these parameters can only be dealt with in qualitative terms in this case. It is obviously difficult to rank parameters which are expressed only on a qualitative basis.

Summary

In view of the many reasons which make it difficult to rank the four evaluation parameters, the draft proposal in Appendix A merely discusses each criterion in qualitative terms, but does not attempt to establish their relative importance in quantitative terms

8.0 Recommendation for Further Study

As a result of this contract, specific computer simulation procedures have been recommended for the measurement of Compression Factor (CF) and Error Sensitivity Factor (ESF). As a recommendation for further study, it is proposed to write the computer programs to perform these measurements on actual imagery data. An Executive routine would be written to control the overall program operation. Three subroutines would be written which are summarized in the table below.

Subroutine No.	Function Simulated	Input	Output
1	Encoder	Input Image Tape	• Compression Factor • Tape with Transmitted Code (T1)
2	Transmission Errors	• T1 • Error Pattern	• Tape with Received Code (T2)
3	Decoder	T2	• Error Sensitivity Factor • Output Image Tape

Following the running of the three subroutines described above the Output Image Tape would be converted to visual form. It is proposed to simulate the one-dimensional code which has been chosen as a standard by the EIA Facsimile subcommittee. Since a great deal of prior simulation work has been done on this code, it would provide an ideal vehicle for cross-checking and verification of simulation accuracy.

Appendix A

Draft Copy of "Criteria for the

Evaluation of Two-Dimensional Coding

Techniques for use in Digital Facsimile Terminals"

Internationale Telegraph and Telephone
Consultative Committee
(CCITT)

COM XIV - No.

Period 1977-1980

Original: English

Date: December 1978

Questions: 2/XIV

STUDY GROUP XIV - CONTRIBUTION No.

SOURCE: UNITED STATES OF AMERICA

TITLE: CRITERIA FOR THE EVALUATION OF TWO-DIMENSIONAL CODING TECHNIQUES
FOR USE IN DIGITAL FACSIMILE TERMINALS

1.0 Summary

This document proposes the use of four criteria for the evaluation
of two-dimensional coding techniques for use in digital facsimile ter-
minals.

- Compression Factor

- Error Sensitivity Factor

- Cost of Implementation

- Commonality with other Facsimile Codes

The proposed criteria are applicable for both Group 4 machines and the
optional extension of the Group 3 machine to include a two-dimensional
code. The proposal is applicable for both the normal resolution (3.85
lines/mm) and high resolution (7.7 lines/mm) scanning standards.

2.0 Background

The CCITT is actively reviewing and considering the standardization
of two-dimensional coding techniques for the optional extension of the
Group 3 one-dimensional code[1]. In the future, consideration will also be
given to coding techniques for Group 4 apparatus[2]. Several papers have
been published recently describing particular two-dimensional coding

techniques and their performance in terms of compression ratio and error
sensitivity.[3,4,5] Unfortunately, it is difficult to compare the results of
different coding techniques and different investigators because the per-
formance measurements are frequesntly not carried out under the same con-
ditions. The primary purpose of this document is to define a set of prag-
matic test conditions in sufficient detail so that all organizations that
wish to have a coding technique selected as a standard by the CCITT will
have a specified procedure to follow to insure all proposals will be eval-
uated on a common meaningful basis.

Much has been proposed to the CCITT and published in the literature
relative to the subject of this paper. This proposal has attempted to draw
upon and integrate this prior work as much as possible. Section 4.0 is a
list of References which have been particularly noteworthy and helpful.

3.0 Proposed Criteria

3.1 Compression Factor

3.1.1 Test Documents

Experimenters in the field of facsimile data compression have utilized
a wide range of test documents to measure compression ratio and error
sensitivity. The 8 CCITT test documents have achieved a wider range of
acceptance than other documents and are somewhat representative of the
pages likely to be transmitted through digital facsimile systems. Con-
sequently, the 8 CCITT documents have been selected for use in the eval-
uation process described herein. The French PTT Administration has scanned
these 8 CCITT documents at both the standard and high resolutions as
specified for Group 3 machines. They have also quantized each pel to be
either black or white and stored the resultant image on magnetic tape.

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Further, the French PTT has provided copies of these tapes to experimenters in the data compression field so that facsimile performance data can be compared on a meaningful basis. For these reasons, it is recommended that the measurements proposed herein be performed using the tapes supplied by the French PTT Administration.

3.1.2 Measurement of Compression Factor (CF)

Any proposed encoding technique must be fully defined in sufficient detail to permit other investigators to duplicate the performance measurement process. The Compression Factor (CF) will be determined for each of the 8 CCITT test documents and for both the standard and high resolution.

The first step in the measurement process is to simulate the encoding function and accumulate a count of the code bits required to transmit each document. The CF for each document is then computed by dividing the total number of picture elements (pels) per test page* by the number of transmitted code bits.

Two different compression factors will be determined. The first establishes the CF of the basic algorithm and excludes synchronization and fill bits from the transmitted code bits. This parameter is not only useful to represent the performance of the basic algorithm but also closely approximates the actual compression performance which will be achieved when operating in a Group 4 configuration. For this reason the compression factor is designated CF_4.

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* The picture tapes from the French PTT contain the following pels:

Standard Resolution - (1064 lines)(1728 pels/line) = 1,838,592 pels

High Resolution - (2128 lines)(1728 pels/line) = 3,677,184 pels

The second compression factor parameter (CF_3) is designed to represent the compression ratio when the algorithm is employed in a typical Group 3 machine. In this case all synchronization bits such as the beginning-of-message, end-of-line, end-of-message, and fill bits are included in the code bits. Fill bits will be generated assuming a minimum line transmission time of   ms, and a transmission bit rate of 4800 bits/sec.

3.2 Error Sensitivity

This section describes the criteria for evaluating the sensitivity of two-dimensional coding techniques to transmission errors. The criteria are valid for Group 3 machines. Measurement of error sensitivity is required for standard resolution (3.85 lines/mm) and for high resolution (7.7 lines/mm).

To evaluate the error sensitivity, both the coding technique and the decoding algorithm must be completely defined and disclosed in sufficient detail to permit computer simulation by any experimenter. If more than one decoding algorithm is proposed (for example, to achieve differing levels of error control), each must be tested separately and fully disclosed.

Both an Objective Measure and a Subjective Measure of error sensitivity will be provided. The Objective Measure will provide a numerical estimate of error-sensitivity, while the Subjective Measure will provide pictorial material for committee evaluation.

3.2.1 Objective Measure

The Objective Measure of error sensitivity is obtained by selecting test documents, encoding them with the proposed technique, subjecting the

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resulting bit stream to transmission errors, decoding the transmission to obtain the received image, and comparing the original image with the received image to determine the number of pels in error.

3.2.1.1 Test Documents

The Test Documents to be used for the error sensitivity test are CCITT Test Documents 1 and 4. Each of the documents would be coded according to the proposed coding technique. Synchronization and fill bits will be included. This encoding will have been done as part of the measurement of Compression Factor for Group 3 Machines (see section 3.1.2).

3.2.1.2 Error Patterns

A record will be provided of actual bit errors made over telephone lines. This will be obtained by transmitting a known psuedorandom sequence at 4800 bits/sec. using a V27 ter modem over a switched telephone network. The average bit error rate will be approximately 1×10^{-3} (between 7×10^{-4} and 1.4×10^{-3}), and the length will be at least 10^6 transmission bits (corresponding to about 3.5 minutes of transmission time). Measurements of this type have already been made by the Federal Republic of Germany[4,6,7] and may be available to experimenters for this purpose. The measured error pattern will be converted to the bit locations of errors and can be supplied on magnetic tape or punched cards.

The supplied error pattern is applied to the encoded transmission, causing a bit reversal at each point where an error is indicated. There will be three runs for each normal resolution (3.85 lines/mm) test document. For the first run, the first bit of the error pattern is aligned with the first bit of the encoded transmission. For subsequent runs, the trans-

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mission is delayed 1,024 bits relative to the previous run so as to obtain
a different phasing of errors relative to critical code words. A count is
made of the number of errors that actually impinge on each transmission.

3.2.1.3 Decoding Transmission

The transmission containing errors is then decoded by the proposed
decoding algorithm to produce a received image. The decoding algorithm
should define the polarity of every pel in the output image. If it does
not for any reason define a pel, it will be arbitrarily set to white.
Note that any error correction schemes may be used providing they are fully
disclosed as part of the proposed coding techniques.

3.2.1.4 Error Calculation

Each pel of the received image is compared to the corresponding pel
in the original image to determine if it matches, or if it is in error.
A count of the number of pels in error is made. In general, there is one
scan line in the output image for every line in the input image. Occasion-
ally, however, a transmission will cause an entire line to be dropped, or
an extra line to be added. When this occurs the comparison algorithm will
assess the appropriate error count for the first time that the original
line is matched against a different line in the received image. After this,
the corresponding lines will be compared. This will prevent a line count
error, which is barely noticeable, from causing a large number of errors
on the rest of the page.

The Error Sensitivity Factor (ESF) is calculated as the total number
of pels in error divided by the total number of transmission bits that are
in error. This calculation is performed for each run of each test document.

The average ESF for each test document is calculated as:

$$ESF_{avg} = \frac{ESF_1 + ESF_2 + ESF_3}{3}$$

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In order to determine the statistical significance of the average ESF, the estimate of the standard deviation of the average ESF is calculated as:

$$\sigma_\ell = \left[\frac{(ESF_1)^2 + (ESF_2)^2 + (ESF_3)^2 - 3(ESF_{avg})^2}{6} \right]^{\frac{1}{2}}$$

The standard deviation of the estimate of the ESF is useful as a check on the adequacy of the sample size and gives an indication of whether measured differences between the ESF's of contending coding techniqes are statistically significant. As a rule of themb, the difference between the average ESF's should be equal to or greater than the sum of their standard deviations to be considered statistically significant.

3.2.1.5 High Resolution Simulation

The Error Sensitivity Factor will be determined for high resolution date by performing only two simulation runs rather than three. This is justified due to the greater number of bits in the high resolution image. In this case the standard deviation is calculated as:

$$\sigma_h = \left[\frac{(ESF_1)^2 + (ESF_2)^2 - 2(ESF_{avg})^2}{2} \right]^{\frac{1}{2}}$$

3.2.2 Subjective Measure

Each of the ten received images generated for the Objective Measure will be made into a hard-copy image using a high-quality (high-resolution, high contrast) process. It is hoped that a common facility will become available for reproducing high-quality images from magnetic tape, or that a recommendation will be made for a suitable machine to be used by experimenters.

The images will be evaluated by the committee to determine the subjective nature of the errors. This will include how noticeable the errors are, how objectionable they are, and an overall judgement of image quality.

3.3 Cost of Implementation

The cost to implement the candidate coding techniques is one of the important parameters in the selection process. Unfortunately, it is unrealistic to expect, or request, equipment design information from organizations proposing a compression algorithm. In addition, different vendors of facsimile equipment would probably implement a given algorithm in a variety of different ways depending upon the volume of manufacture and other factors. Having recognized the difficulty of quantitatively measuring this parameter, there are two general comments listed below which apply.

- Most of the circuitry used to implement the candidate coding is digital and consequently benefits from the continuous cost reduction of digital components. Therefore, the cost differential between alternative techniques will probably diminish with time.

- It is essential that a proposed coding technique be internationally available, free of any royalty considerations.

3.4 Commonality with other Facsimile Codes

3.4.1 Group 3 / Group 4 Compatibility

It is possible that the ideal code for the Group 4 machine would differ from the ideal code for the Group 3 extension from the one-dimensional code. However, it is desirable to select one standard two-dimensional code which would be used in both systems in order to achieve machine compatibility. The objective would be to select a code which provides the best overall performance for both Group 3 and Group 4 system configurations.

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It is very critical for the two possible Group 3 machines (one-dimensional code, and two-dimensional code) to be compatible. To minimize the cost of this compatibility it would be desirable to select a two-dimensional code which is based upon an extension of the one-dimensional code as much as possible.

3.4.2 Machines with Greater Document Width

It is desirable to select a compression algorithm which can be economically extended for application to documents wider than that for the Group 3 machines. For example, it may be desired to double the document width so that a total of 3,456 pels/line would be transmitted. It would be advantageous for the code for the wide document to be merely an extension of the normal width code for reasons of compatibility and cost minimization.

3.5 Relative Importance of the Criteria

One major purpose of this document is to assist persons or committees in selecting a standard facsimile coding algorithm. Toward this end, it would be very helpful to rank the four evaluation criteria in terms of their relative importance. Unfortunately, this is very difficult to do because of the widely varying perspectives and orientations of different committees and committee members. For example, it is inevitable that facsimile manufacturers and common carrier organizations would view the evaluation parameters differently. In addition, the market orientation of a vendor will greatly affect his position on the evaluation criteria. For example, a company which manufactures high volume products which stress conventional picture quality would view the situation very differently from a vendor who stresses the low volume/high quality market. Having

recognized the difficulty of precisely ranking the criteria, the following
general comments are provided for each of the evaluation parameters.

Compression Factor

It is very possible that the Compression Factors of the candidate
compression techniques will not vary widely, in which case this parameter
may not be critical in the decision process. If, however, one coding
alternative exhibits an unusually high or low Compression Factor, this
parameter would obviously become important.

Error Sensitivity

The Error Sensitivity Factor is much more important for Group 3
machines than Group 4 machines due to the different transmission error
rate conditions. This parameter is particularly difficult to rank due to
the potential high degree of interaction with other evaluation criteria.
For example, some facsimile systems can automatically reduce the transmission
rate to the point where an acceptable error rate is achieved. This results
in a trade-off between error sensitivity and compression.

Another trade-off could exist between error sensitivity and implementa-
tion cost. At one extreme could be a compression system which is very sen-
sitive to transmission errors but which employs a very complex post-decoder,
error-reduction scheme to minimize the visual effect of errors. At the
other extreme could be a coder which inserts sufficient redundancy into the
transmitted code to correct for some transmission errors. In this case,
the system is relatively insensitive to channel errors, may be less
expensive, and would have a reduced compression ratio.

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Cost of Implementation

This parameter could become important for some candidates which involve very complex error correctors or large buffers. Again, it is critical that selected coding techniques be free of any royalty considerations.

Compatibility with other Facsimile Machines

It is desirable that the two-dimensional code selected for the optional extension from Group 3 be also adopted for Group 4 application. Further, it is highly desirable that the structure of this two-dimensional code be as similar as possible to the one-dimensional Group 3 code and that it be extendable to greater document widths.

Tabulation of Quantitative Evaluation Criteria

Table 1.0 is a form for the tabulation of the quantitative evaluation criteria - Compression Factors and Error Sensitivity Factors.

PARAMETER		VERT. RESOL. $\frac{\text{lines}}{\text{mm}}$	CCITT TEST DOCUMENT NO.							
			1	2	3	4	5	6	7	8
COM- PRESSION FACTOR (CF)	CF$_3$	3.85								
		7.7								
	CF$_4$	3.85								
		7.7								
ERROR SENSI- TIVITY FACTOR (ESF)	PHASE 1	3.85								
	PHASE 2	3.85								
	PHASE 3	3.85								
	PHASE 1	7.7								
	PHASE 2	7.7								

TABLE 1.0 TABULATION OF QUANTITATIVE EVALUATION CRITERIA

4.0 References

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2. United States of America, "Guidelines to Establish Standardizations of Group 4 Apparatus," CCITT Study Group XIV - Contribution No. 36, June 1978.

3. Japan, "Proposal Concerning Selection of Two-Dimensional Coding System for Redundancy Reduction," CCITT Study Group XIV - Contribution No. 15, Sept. 13, 1977.

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10. Special Rapporteur, "Minutes of Meeting of the Special Rapporteur Group on Group 3 Machines held in Paris from 2 to 5 November 1976," CCITT Study Group XIV - Contribution No. 7, March 1977.